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Veijo Kaitala, Karl-Göran Mäler, and Henry Tulkens

Box 50005, 104 05 Stockholm, Sweden
Tel: +46-8-673 95 00, Fax: +46-8-15 24 64

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The Royal Swedish Academy of Sciences
Box 50005, S-104 05 Stockholm, Sweden
Telephone +46(0)8-673 95 00, Telefax +48(0)8-15 24 64
E-mail: BEIJER @ BEIJER.KVA.SE

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The acid rain game as a resource allocation process with an application to the international cooperation among Finland, Russia, and Estonia*

V. Kaitala **,***, K.-G. Mäler **, and H. Tulkens ****

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** The BEIJER International Institute of Ecological Economics, The Royal Swedish Academy of Sciences, Box 50005, S-10405 Stockholm, Sweden
*** Systems Analysis Laboratory, Helsinki University of Technology, Espoo, Finland
**** C.O.R.E., Universite Catholique de Louvain, 34 Voie du Romain Pays, B-1348 Louvain-la Neuve, Belgium

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Abstract. We consider optimal cooperation in transboundary air pollution abatement among several countries under incomplete information. The countries negotiate on establishing a gradual cooperative emission reduction program to reduce the damages caused by sulphur depositions. Local information available on the marginal emission abatement costs and damage costs allows one to determine directions of emission abatement in each country that converge to an economic optimum. **A** particular difficulty arising here is how the partners can guarantee that the costs and benefits from cooperation will be shared in such a way that none of them will be tempted to breach the agreement. To overcome this problem we make use of a cost sharing scheme proposed by Chander and Tulkens (1991), that results from appropriately designed international transfers. This scheme guarantees that the individual costs of all parties are nonincreasing along the path towards the optimum, and that no party or group of parties has an interest in proposing another abatement policy. The paper illustrates these methods by applying them to a three-country version of Maler's (1989) "acid rain game", tailored to numerically simulate the negotiations on sulphur emissions abatement between Finland, Russia and Estonia.

1 Introduction

We consider in this paper the problem of cooperation on transboundary air pollution abatement among several countries. In contrast to the full information approach used by Maler (1989), we use here a formulation in which the countries have only partial information available when they negotiate on establishing cooperative emission abatement programs to reduce the damages caused by pollution, as in Tulkens (1979). It is assumed in particular that only "local" information is available on the emission abatement costs and on the damage costs caused by the pollution depositions. By local information we mean the current values of the marginal emission abatement costs and of the marginal depositions damage costs. Such local information is sufficient to determine current emission abatement actions to be taken in each country at any time, that converge to an economic (Pareto) optimum.

This methodology has its origin in the theory of resource allocation processes initiated in 1960 by Arrow and Hurwicz (see Arrow and Hurwicz (1977)) and applied later on to public goods by e.g. Dreze and de la Vallee Poussin (1971), Malinvaud (1971) and most recently by Chander (1993).

The optimum so determined can only be a cooperative one if it guarantees the partners that none of them will be forced to pay for environmental cooperation more than is reasonable. To this effect, and Chander and Tulkens (1991, 1992) have devised a cost sharing scheme, accompanied by international transfers, that guarantees that the individual costs of all parties are nonincreasing along the path to the cooperative optimal solution, and that no subset of them has an interest to follow another course of action.

This paper demonstrates the applicability of these methods in a three-country acid rain negotiation problem among Finland, Russia, and Estonia.

2 Achieving optimality in the acid rain problem

In this section, we first characterize optimality assuming that full information is available for the players. We then formulate a means to approach the optimal solution by using the local information only. The scheme is illustrated by an example related to the sulphur negotiations among Finland, Russia, and Estonia analysed in detail by Kaitala and Pohjola (to appear). Cooperation issues are dealt with in section 3.

2.1 Optimality

Let $E = (E_1, ..., E_n)^T$ denote the emissions, $Q = (Q_1, ..., Q_n)^T$ the depositions, and $B = (B_1, ..., B_n)^T$ the background depositions. Furthermore, let $A = (a_{ij})$ denote the transportation matrix. In particular a_{ij} denotes the fraction of emission E_j that deposits in area i. As in Mäler (1989) let the emission-deposition interaction be presented as

$$Q_i = \sum_{j=1}^{n} a_{ij} E_j + B_i \qquad (1)$$

for all i, or in the matrix form

$$Q = AE + B.$$

Furthermore, let $C_i(E_i)$ denote a function that associates the total costs of aggregate productive activity in country i with the level of emissions E_i taking place there. For this function we assume that $C_i'(E_i) < 0$ in the relevant range, reflecting the fact that increased emissions allow for lower production costs or, taking the derivative to the left, that reducing emissions increases production costs.

Let also the function $D_i(Q_i)$ denote the total costs entailed in country i by the damages caused there by the depositions Q_i. The natural assumption here is that $D_i'(Q_i) > 0$.

Let finally

$$J_i = C_i(E_i) + D_i(Q_i(E)) \qquad (2)$$

denote the aggregate for country i of the two categories of costs just defined. All these costs are assumed to be measured in some common units.

Consider now the optimization problem

$$\min_{E_1,\dots,E_n} J = \sum_{i=1}^{n}\Big(C_i(E_i) + D_i(Q_i(E))\Big) \tag{3}$$

such that (1) be satisfied. The optimality conditions are

$$C_i'(E_i) + \sum_{j=1}^{n} a_{ji} D_j'(Q_j(E)) = 0,\ i = 1, ..., n. \tag{4}$$

We assume that the solution to problem (3) exists and is unique. Finding such a solution, in a way that in addition satisfies all i's, is what Mäler referred to as the "Acid Rain Game". In this section we deal only with the optimality aspect; game theoretic aspects will be introduced in section 3.

2.2 Path to the optimal solution

Computing the solution that meets the optimality conditions above requires that the countries have full information about their entire emission abatement cost functions as well as about their entire cost functions of the damages caused by sulphur depositions. However, when the actual environmental conditions that prevail in the countries are far from the level that can be considered as optimal, then these costs may be very difficult to estimate, since the emission and deposition levels would change widely. This lack of information might make it impossible for the countries to negotiate cooperative environmental agreements that could satisfy the optimality condition (4).

To overcome this difficulty Tulkens (1979) proposed that the countries use only *local* information to establish a *gradual* emission abatement program towards the optimal emission levels implied by (4). He showed that in spite of the absence of full information, the local information is sufficient to guarantee that the changes in the emissions are towards the optimal levels.

Specifically, assume as in Mäler (1989) that the pollution policies by the countries are initially selfish and such that their emission levels correspond to a non-cooperative Nash equilibrium emissions levels $\bar{E}_i$. Assume further that local information on the cost functions — that is, on the marginal emission abatement costs $C_i'(E_i)$ and the marginal damage costs $D_j'(Q_j(E))$ — are available at the initial level $\bar{E}$. The value

$$\sum_{j=1}^{n} a_{ji} D_j'(Q_j(E)) + C_i'(E_i)$$

at any nonoptimal initial emission level $\bar{E}$ may be seen as the aggregate cost savings – thus the willingness to pay – of all countries j for a marginal reduction of country i's emissions E_i, net of the cost $C'(E_i)$ of this reduction (as we speak of *reductions*, given the signs of D_i' and C_i' defined above, the first term in the last expression is negative and the second one is positive).

On that basis, an emission reduction program of the Tulkens (1979) type can be presented in the continuous time setting as follows

$$\frac{dE_i}{dt} = \dot{E}_i = -K\Big(C_i'(E_i) + \sum_{j=1}^{n} a_{ji} D_j'(Q_j(E))\Big), \quad E_i(0) = \bar{E}_i, \tag{5}$$

$$\dot{Q}_i = \sum_{j=1}^{n} a_{ij} \dot{E}_j, \quad Q_i(0) = \sum_{j=1}^{n} a_{ji} \bar{E}_j + B_j, \quad i = 1, \ldots, n. \tag{6}$$

where $K > 0$ is a constant, and $\bar{E}$ is an initial Nash noncooperative emission level vector. Thus, the solution of the optimality problem is obtained by integrating (5) - (6) in time. Note that changing the value of K corresponds to changing the time scale such that increasing K makes the speed of changes to increase.

2.3 Example: Finland, Russia, and Estonia

Consider now as an application of the approach the problem of optimal cooperation on transboundary air pollution abatement among Finland, Russia, and Estonia analysed in detail by Kaitala and Pohjola (to appear). In this model Finland and Russia have been divided into three areas whereas Estonia has been treated as one area (for the indexes, see Table 1). The sulphur emissions, E, the total depositions, Q, and the background depositions, B in 1987 are given in Table 1, while the sulphur transportation matrix is given in Table 2 (both tables are taken from the paper just quoted, where details and further references are given).

The authors use the following functional forms for the cost and damage functions:

$$C_i(E_i) = \alpha_i(\bar{E}_i - E_i) + \beta_i(\bar{E}_i - E_i)^2 + \gamma_i \tag{7}$$

and

$$D_i(Q_i) = \pi_i Q_i \tag{8}$$

whose parameter values are given in Table 3.

The estimates of the parameters of the annual emission abatement cost functions (α, β and γ in Table 3) are based on an extensive work carried out by the Finnish Integrated Acidification Assessment (HAKOMA) project at the Technical Research Center of Finland (Johansson, Tähtinen and Amann 1991) with the purpose to evaluate abatement costs in emission source that are relevant to the acid rain problem in Finland.

Table 1: Sulphur emissions, depositions, and background depositions in 1987 (1 000 tons per year)

	i	E_i	Q_i	B_i
Northern Finland	1	5	46	26
Central Finland	2	60	98	59
Southern Finland	3	97	66	35
Kola	4	350	131	27
Karelia	5	85	95	50
St Petersburg	6	112	88	46
Estonia	7	104	60	32

Table 2: Sulphur transportation matrix A for the year 1987

		Emitting region (j):						
		NFin 1	CFin 2	SFin 3	Kol 4	Kar 5	Len 6	Est 7
Receiving region (i):								
Northern Finland	1	.200	.017	.010	.046	.012	.000	.000
Central Finland	2	.000	.300	.062	.011	.047	.036	.029
Southern Finland	3	.000	.017	.227	.003	.000	.027	.038
Kola	4	.000	.017	.000	.286	.023	.009	.000
Karelia	5	.000	.033	.031	.017	.318	.045	.019
St Petersburg	6	.000	.017	.031	.003	.012	.268	.058
Estonia	7	.000	.000	.031	.000	.000	.018	.221

Table 3: Emission abatement cost function parameters α (FIM/kg S), β (FIM/ton^2), and γ (10^6 FIM), and marginal damage costs π (FIM/kg S)

	α	β	γ	π
Northern Finland	10.0	2.093	5.9	50.0
Central Finland	3.8	0.172	33.0	8.9
Southern Finland	4.6	0.068	53.6	15.6
Kola				
- for $98 < E_4 \leq 350$:	1.0	0.0	0.0	2.6
- for $0 < E_4 \leq 98$:	1.0	0.077	252.0	
Karelia	4.0	0.045	0.0	11.6
St Petersburg	6.0	0.051	0.0	20.2
Estonia	2.0	0.015	0.0	2.8

However, less reliable estimates are available on the damage costs (π in Table 3) caused to forestries by sulphur depositions. A rough attempt has been made to directly estimate the losses caused to forestries by soil acidification (see Kaitala, Pohjola and Tahvonen 1991). These direct estimates may fail, however, to capture other essential damages that also affect the willingness-to-pay. For that reason, the damage function parameters that we shall use will be obtained from an indirect method of "revealed preference" that was proposed by Mäler (1990).

In 1987 the governments of Finland and USSR signed an agreement with the purpose of limiting their sulphur emissions and reducing the depositions on a cooperative basis. Thus, 1987 was a year that could be characterized as a Nash equilibrium between Finland and the USSR. At a Nash equilibrium each country emits sulphur until her marginal emission abatement costs are equal to her marginal damages caused by sulphur depositions (Kaitala and Pohjola, to appear). This observation suggests that at this equilibrium at least, marginal damage costs (π_i) of each country are revealed by just observing their respective marginal abatement costs. These are the values reported for π in Table 3.

However in 1987 the USSR was still in existence, with Estonia belonging to it. Now, Estonia has regained her independence and, unlike Russia, does not recognize the agreements signed by the former USSR. Consequently, in the new political situation the environmental policy would change in Estonia if her own marginal willingness to pay were to be different from what it was under the soviet regime. As we have no indication so far of any major changes in the environmental policy in Estonia, we think it justified to keep using the damage function estimate derived for the socialist Estonia for our illustrative purposes.

Applying the functional forms (7) and (8) in (5) we get

$$\dot{E}_i = -K\Big(-\alpha_i - 2\beta_i(\bar{E}_i - E_i) + \sum_{j=1}^{n} a_{ji}\pi_j\Big), \; E(0) = \bar{E}. \tag{9}$$

Figures 1 and 2 illustrate the values $E_i(t)$ and $Q_i(t)$ along the solution of the system (9), thus describing the "path" over time towards an environmental optimum among the three countries. The simulations are carried out assuming that the parameter estimates given in Table 3 are correct. Thus, the simulations represent a single possible outcome of the cooperative game. Deviations from this solution would occur if the marginal willingness to pay were to deviate from the one estimated. In the figures the time horizon is 150 years. Note, however, that taking $K = 10$ we get the same results in a time scale of 15 years.

Sizeable emission reductions occur in Kola and in Estonia (76.6 and 44.2 percent, respectively), and minor emission reductions are also carried out in the remaining areas (3.3-12.9 percent; for more numerical details, see Table 5 of Kaitala and Pohjola, to appear) except in Northern Finland where no reductions are observed (see Figure 1). The main reason for the high emission reductions in Kola is that the estimated marginal damage value of the neighboring Northern Finland is about twenty times higher than that of the Kola region. Moreover, the marginal emission abatement costs are lowest in Kola and highest in Northern Finland; Similarly, notable amounts of Estonian emissions are transported to St. Petersburg and Southern Finland, whose marginal damage values are 5-7 times higher than that of Estonia and the emission abatement costs of Estonia are lower than those in St. Petersburg and Southern Finland.

The obvious kinks in the emission trajectories of Kola and Estonia are due to the corresponding kinks in their marginal emission abatement costs (see Table 3 of Kaitala and Pohjala, to appear). The reason for the absence of emission abatement in Northern Finland is that this area does not contribute to the depositions in any other region. Thus, the noncooperative and cooperative emissions of that area are equal.

Depositions are illustrated in Figure 2. Thus, the reductions in depositions are strongest in Kola (59 %), Northern Finland (26 %), and Estonia (18 %). In Karelia the reductions are 10 %, and in the three remaining area 6-7 %. The final depositions in areas 1-7 stabilize at the levels 0.33, 0.54, 1.16, 0.37, 0.50, 0.95, and 1.10 Sg/m^2 respectively. Thus, from the point of view of critical loads the high depositions in Southern Finland (1.16), St Petersburg (0.95), and Estonia (1.10) may not be acceptable.

3 Individual rationality, group rationality, and cooperation

We now turn to study the gains — that is, the aggregate cost reductions — that the countries or the areas receive from achieving this optimum. Let $\bar{J}_i$ denote the costs at the Nash equilibrium and let $\tilde{J}_i(t)$ denote the costs at time t. Denote further the gains at time t as $J_i(t) = \tilde{J}_i - \bar{J}_i$ and $J(t) = \sum_i J_i(t)$. Obviously $J_i(t)$ measures the cost reduction that area i enjoys due to the cooperation as compared to the original Nash situation. Since the costs at the Nash equilibrium are constant

FIGURE 1: EMISSIONS

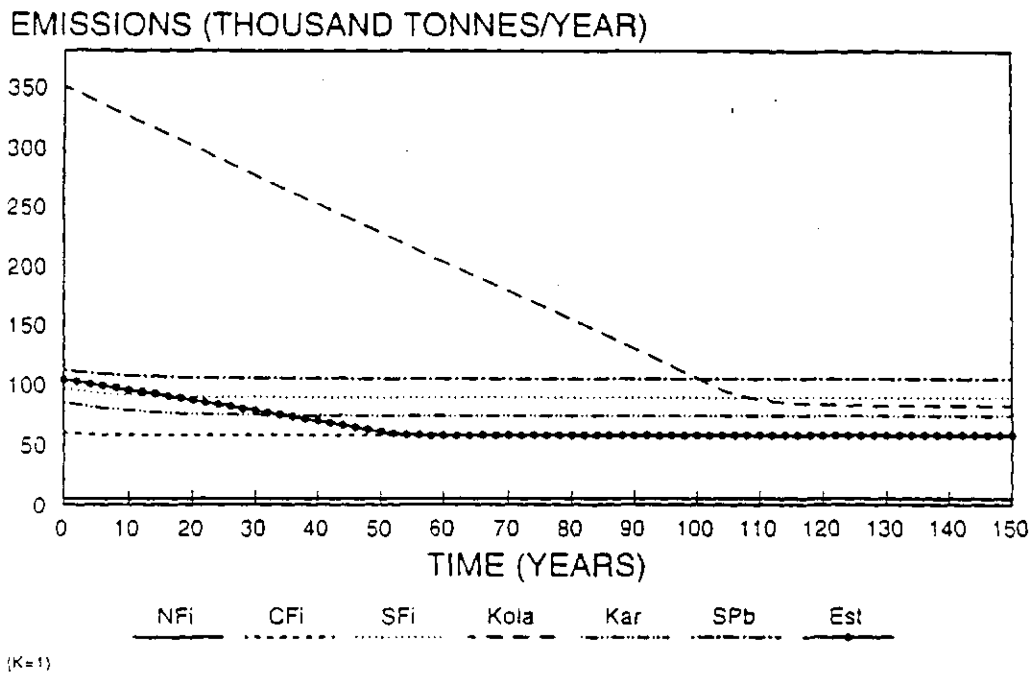

Figure 1: Path of sulphur emissions in Finland, Russia and Estonia. Reductions occur everywhere at the start, and only in Kola and in Estonia thereafter.

FIGURE 2: DEPOSITIONS

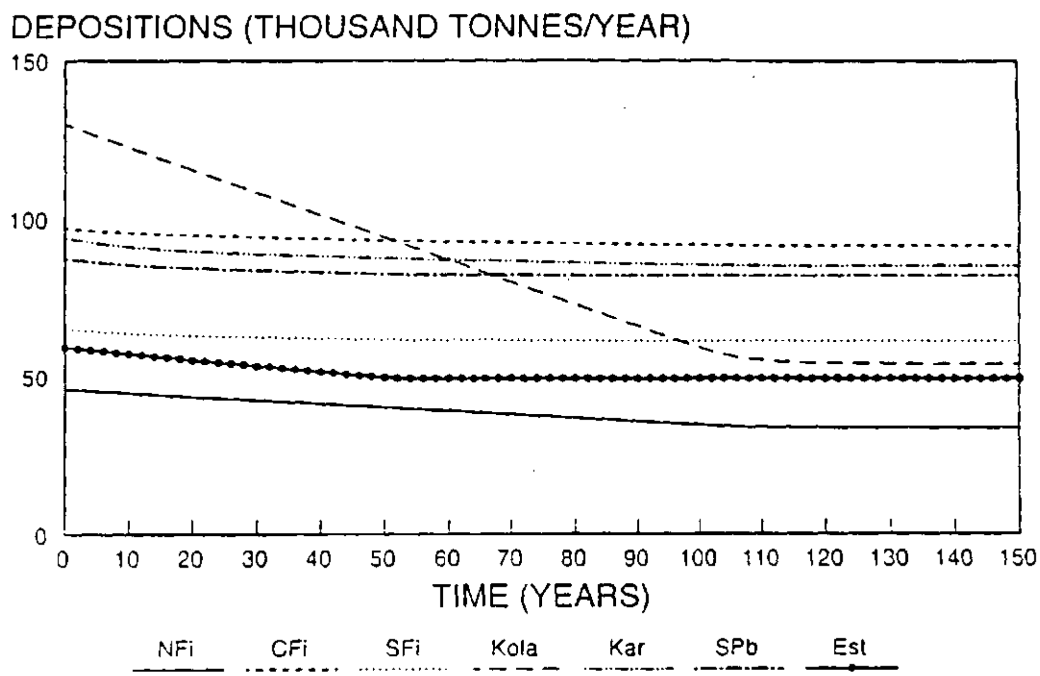

Figure 2: Path of sulphur depositions in Finland, Russia and Estonia. Reductions occur everywhere at the start, and in Kola, Estonia and Northern Finland thereafter.

then $dJ_i(t)/dt = d\tilde{J}_i(t)/dt$.

We have

$$\dot{J} = \sum_{i=1}^{n}\Big(C_i'(E_i)\dot{E}_i + D_i'(Q_i)\dot{Q}_i\Big) \tag{10}$$

or, using (6),

$$\dot{J} = \sum_{i=1}^{n}\Big(C_i'(E_i)\dot{E}_i + D_i'(Q_i)\sum_{j=1}^{n} a_{ij}\dot{E}_j\Big)$$
$$= \sum_{i=1}^{n}\Big(C_i'(E_i)\dot{E}_i + \sum_{j=1}^{n} a_{ji}D_j'(Q_j)\dot{E}_i\Big)$$

or still, using (5),

$$\dot{J} = -\frac{1}{K}\sum_{i=1}^{n}\dot{E}_i^2 \leq 0 \tag{11}$$

with $J(0) = 0$. Thus, the direction is towards the global minimum at each time moment.

3.1 Individual rationality

Two problems arise, however. First, (11) does *not* imply that $\dot{J}_i < 0$ for each i. Thus it may happen that the individual aggregate costs for some players increase along the solution and end up being higher at the optimum than they are at the Nash equilibrium. That is the case in the present numerical application illustrated in Figure 3, where one sees that indeed Kola and Estonia do incur, at the optimum, annual costs of 87 and 64 million FIM, respectively, above the cost associated with the initial Nash equilibrium solution. Such an outcome is likely to prevent Kola and Estonia from joining in the abatement program specified by the solution to (9).

To induce cooperation, it has often been proposed in the literature (see e.g. Tulkens 1979, Mäler 1990, Kaitala et al. 1992a,b) to make use of transfer payments between the countries involved. This will be done in the present model by adding to each aggregate cost function (2) a transfer payment variable T_i (> 0 if the transfer is paid out by i, and < 0 if it is received by it). Imposing the constraint

$$\sum_{i=1}^{n} T_i = 0 \tag{12}$$

FIGURE 3: AGGREGATE COST CHANGES ($J = C + D$)

WITH NO TRANSFER PAYMENTS

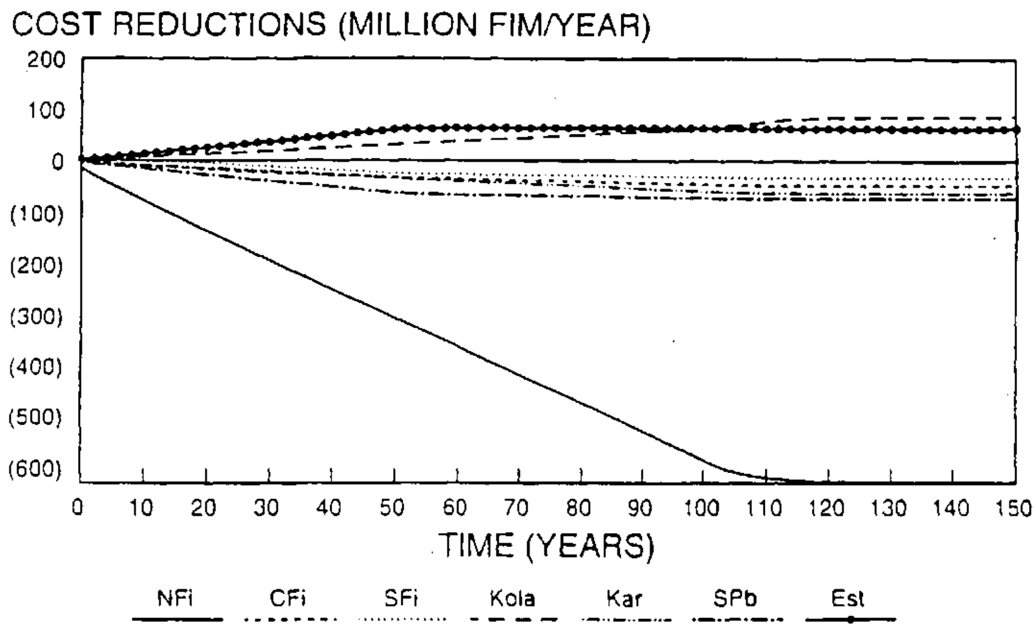

Figure 3: Along the path to the environmental optimum the aggregate $C + D$ costs are reduced in St Petersburg, Karelia, and in all areas of Finland. The costs reductions are particularly high in Northern Finland. However, Kola and Estonia see their aggregate costs increase as compared with the initial Nash equilibrium solution which will jeopardise their cooperation in achieving the optimum.

ensures that these transfer payments are feasible, i.e., that the budget of an international agency established to implement them would be balanced.

The optimization problem (3) then becomes

$$\min_{E_1,\ldots,E_n,T_1,\ldots,T_n} J = \sum_{i=1}^{n} J_i(E,T_i) = \sum_{i=1}^{n}\Big(C_i(E_i) + D_i(Q_i(E)) + T_i\Big) \tag{13}$$

subject to (1) and (12). The solution is called an "individually rational" optimum if it is such that for each i, J_i at the optimum is lower than at the Nash equilibrium. Notice that optimality conditions (4) are unaffected by this change.

How large should each transfer T_i be to achieve individual rationality? Here arises a second problem. If only local information on the cost and damage functions is available, it is not possible to compute *in advance* a side payment program that leads to a solution individually rational for all parties.

The problem could be solved however if, setting $T_i(0) = 0$ so as to keep $J_i(0) = 0$ for all i , one could find $\dot{T}_i$ depending only upon local information and such that $\dot{J}_i \leq 0$ for all i. This is provided by specifying

$$\dot{T}_i = -\Big(C_i'(E_i)\dot{E}_i + D_i'(Q_i)\dot{Q}_i\Big) - \frac{1}{K}\sum_{j=1}^{n}\delta_{ij}\dot{E}_j^2 \tag{14}$$

for each i, with

$$0 \leq \delta_{ij} \leq 1 \text{ for all } i,j \tag{15}$$

$$\sum_{i=1}^{n}\delta_{ij} = 1 \text{ for all } j \tag{16}$$

from which it follows from (9) and (10) that

$$\dot{J}_i = -\frac{1}{K}\sum_{j=1}^{n}\delta_{ij}\dot{E}_j^2 \leq 0, \quad i = 1,\ldots,n. \tag{17}$$

Clearly, this transfer payment program guarantees that the individual aggregate costs of all parties are nonincreasing along the solution. This property of the system (5), (6) and (14) is called "individual rationality", providing to it a minimal cooperative character.

3.2 Group rationality and cost sharing

A stronger form of cooperation can be obtained, however, by making use of the cost sharing rule proposed by Chander and Tulkens (1991, 1992). It implies in the present model that the parameters δ_{ij} in (15)-(16) be chosen as

$$\delta_{ij} = \frac{a_{ij} D_i'}{\sum_{k=1}^{n} a_{kj} D_k'}, i, j = 1, ..., n. \tag{18}$$

This choice not only guarantees feasibility, that is $\sum_i T_i(t) = 0$ for all t, (as one easily computes from (14), using (18)), as well as individual rationality (since the inequality in (17) is preserved with (18)), but it also possesses – as shown in the 1991 paper just quoted – the cooperative game theoretical property of inducing an imputation in the core of games associated with the solution of (5), (6) and (14). The cooperation thus achieved is claimed to be stronger because it is not only individually rational but also "coalitionally" rational or "group rational".

It is also of some interest to notice that with (18), the expression (14) for the transfers reduces to

$$\begin{aligned} \dot{T}_i &= -\left(C_i'\dot{E}_i + D_i'\dot{Q}_i\right) - \frac{1}{K}\sum_{j=1}^{n} \frac{a_{ij} D_i'}{\sum_{k=1}^{n} a_{kj} D_k'} \frac{1}{K}\dot{E}_j^2 \\ &= -\left(C_i'\dot{E}_i + D_i'\sum_{j=1}^{n} a_{ij}\dot{E}_j\right) - \frac{1}{K}\sum_{j=1}^{n} \frac{a_{ij} D_i'}{\sum_{k=1}^{n} a_{kj} D_k'} \frac{1}{K}\dot{E}_j^2 \\ &= -\left(C_i'\dot{E}_i + D_i'\sum_{j=1}^{n} a_{ij}\dot{E}_j\right) - \sum_{j=1}^{n} \frac{a_{ij} D_i'}{\sum_{k=1}^{n} a_{kj} D_k'}\left(C_j' + \sum_{k=1}^{n} a_{kj} D_k'\right)\dot{E}_j \\ &= -C_i'\dot{E}_i + \sum_{j=1}^{n} \frac{a_{ij} D_i'}{\sum_{k=1}^{n} a_{kj} D_k'} C_j'\dot{E}_j^2. \end{aligned} \tag{19}$$

In this form, the transfer paid out or received by a region i appears to be the algebraic sum of two parts: (i) a first one, which is received by the region to cover the cost of its own emissions abatement $\dot{E}_i$ (first term in (19), which is positive if $\dot{E}_i < 0$); and (ii) a second one, which is paid out by i to each one of the other regions j to share the cost of their emissions abatement $\dot{E}_j$, in the proportion $a_{ij} D_i' / \sum_{k=1}^{n} a_{kj} D_k'$ for each j.

With (19) thus substituted for (18), it becomes clear that our process also implements a rule for sharing the cost of emissions abatement in the regions involved.

3.3 The cooperative solution in the example

We now introduce the transfer payments (14), with (18), in our example related to the acid rain cooperation among the three countries.

Table 4 gives the cost sharing coefficients δ_{ij} as defined by (18). The numbers in each column should add up to 1, as they each represent the fraction of the unit abatement cost in country j that is borne by country i. Referring to the elements a_{ij} of the transport matrix in Table 2, as well as to the values π_i of the marginal damage costs in Table 3 permits one to understand the structure of the numbers in Table 4. For instance $\delta_{11} = 1.000$ because $a_{i1} = 0$ for all i's not equal to 1 in Table 2. On the other hand, diagonal elements dominate (except in two cases) because they also dominated in Table 2. Considering the exceptions, the case of δ_{14} — that is, the fraction of abatement costs in Kola ($j = 4$) borne by Northern Finland ($i = 1$) — is a striking one: it is equal to 0.667, i.e. 2/3 of the total and more than three times what Kola bears itself (i.e. 0.216). This results from the combination, in formula (18), of a relatively large value of a_{14} (0.046 in Table 2), a very large value of π_1 (50.0 in Table 3) and a very low value for π_4 (2.6 in Table 3). A similar argument explains δ_{67}.

Moving now to the adjustment process (5), (6), (14) and (18), Figure 4 illustrates the results in terms of the transfer payments (T), and Figure 5 shows the evolution of each $J_i(t)$ in (13), which are the costs after the side payments are paid/received.

According to the solution Kola and Estonia both do receive international environmental support from Finland. It should be noted that the transfer payments paid by St Petersburg and Karelia are not high enough to cover the transfer payments received by Kola, so that, Russia as a whole is a net receiver of the monetary environmental aid.

From Table 5, where the cost figures at the limit are recorded, one notices that cooperation shows an aggregate gain of about 688 million FIM which, if shared according to the transfers programs (14) with (18), yields the overall cost reductions offered in the third column of the table. The costs reductions are distributed very unevenly among the areas (18.5, 2.6, 1.8, 40.3, 4.0, 1.6 and 4.7 percent of the Nash equilibrium noncooperative costs, respectively). Equal overall cost reductions can also be computed, as in the fourth and fifth columns of the table. Apart from the fact that the outcome is then much less favourable for Finland (in particular, the transfers it makes to Russia and Estonia are much larger), this latter scheme may also not enjoy the cooperative game theoretic properties of the former.

Table 4: Chander - Tulkens (1991)
abatement cost sharing parameters δ_{ij}

i \ j		NF 1	CF 2	SF 3	Kl 4	Kr 5	SP 6	Est 7
NF	1	1.000	.187	.088	.667	.120	.000	.000
CF	2	.000	.586	.097	.028	.084	.047	.090
SF	3	.000	.058	.625	.014	.000	.062	.207
Kl	4	.000	.010	.000	.216	.012	.003	.000
Kr	5	.000	.084	.063	.057	.736	.077	.077
SP	6	.000	.075	.111	.018	.048	.802	.409
Est	7	.000	.000	.015	.000	.000	.007	.216

Table 5: Ultimate cost figures (10^6 FIM)

		with Chander–Tulkens Transfer Scheme		with Cost-Egalitarian Transfer Scheme	
	J_i (eq. (10))	T_i	$J_i + T_i$	T_i^E	J_i^E
Northern Finland	-629	+203	-426	+530.7	-98.3
Central Finland	-46	+23	-23	-52.3	-98.3
Southern Finland	-32	+12	-20	-66.3	-98.3
Finland	**-707**	**+238**	**-469**	**+412.3**	**-294.9**
Kola	+88	-225	-137	-186.3	-98.3
Karelia	-61	+17	-44	-37.3	-98.3
St Petersburg	-72	+42	-30	-26.3	-98.3
Nearby Russia	**-45**	**-166**	**-211**	**249.9**	**-294.9**
Estonia	**+64**	**-72**	**-8**	**-162.3**	**-98.3**
Total -	-840	-297	-688		
Total +	+151	+297	0		
Total	-688	0	-688	0	-688

Table 6 illustrates the sensitivity of the cost sharing scheme with respect to a change in the Estonian marginal damage. The main effect of doubling the Estonian marginal damage ***TTJ*** from 2.8 to 5.6 is that the loss suffered by Estonia at the optimum without transfers is almost halved; Finland remains unchanged and Russia benefits a little (compare the columns 1 in Tables 5 and 6).

The aggregate benefit, measured as the total cost reductions, increases from 688 to 717 million FIM. The difference (29 million FIM) is divided among the countries in such a way that each country gets a share of it, with Estonia getting most of it. Finally, the total transfer payments are slightly reduced (from 297 to 286 million FIM); the transfer payments paid by Finland are reduced, and the relative share from as well as the absolute amount of the transfer payments received by Estonia are both decreased.

As a whole, while an increase in the value of her marginal damage increases Estonia's net benefit as measured by $T + J$, it decreases, however, the amount of the side payment T she finally receives.

Table 6: Sensitivity of the scheme with respect to doubling the Estonian marginal damage (10^6 FIM)

	J_i (from eq. (10))	T_i	$J_i + T_i$
Northern Finland	-629	+203	-426
Central Finland	-48	+23	-25
Southern Finland	-30	+7	-23
Finland	**-707**	**+233**	**-474**
Kola	+87	-224	-137
Karelia	-62	+17	-45
St Petersburg	-73	+36	-37
Nearby Russia	**-48**	**-171**	**-219**
Estonia	**+38**	**-62**	**-24**
Total -		-286	
Total +		+286	
Total	-717	0	-717

FIGURE 4: TRANSFER PAYMENTS

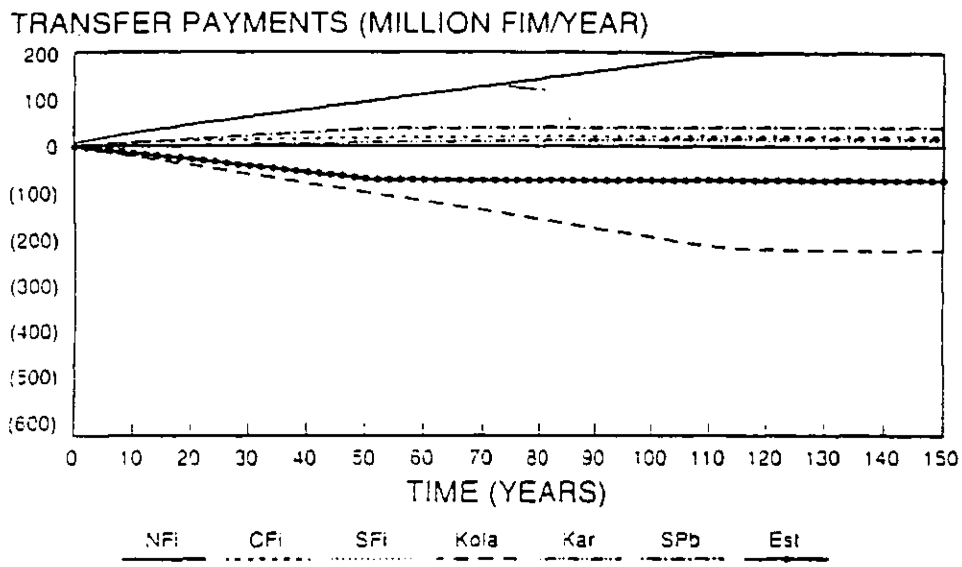

Figure 4: The evolution of the transfer payments over time. To induce their cooperation towards the optimum, Kola and Estonia are compensated by an international environmental aid from Finland.

FIGURE 5: AGGREGATE COST CHANGES (J=C+D)

WITH TRANSFER PAYMENTS

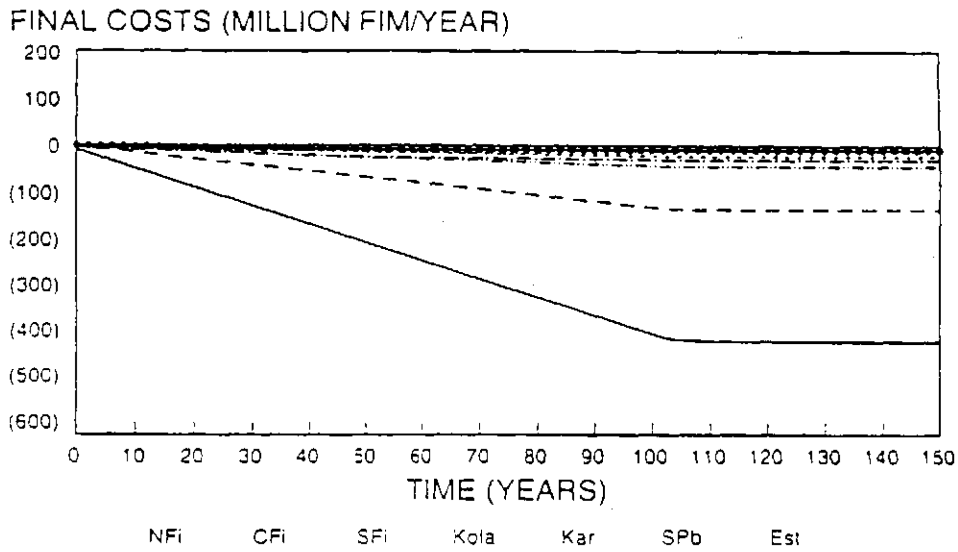

Figure 5: The aggregate cost reductions after the transfer payments. Each area enjoys an aggregate cost reduction from the environmental cooperation under the transfer payment scheme.

4 Increasing marginal damages

It is of particular interest to consider the consequences of different possible formulations of the damage functions, that is, of the willingness to pay in each area. Indeed, this information will actually be revealed only with time, as the emission abatement proceeds and the depositions in each area decrease. Simulations with alternative specifications may however give some idea of how emissions abatement policies are influenced by damage functions.

In this section we deviate from the linearity assumption (8) and study as an alternative the possibility of increasing marginal damages. In particular, assume that the realization of the damage function will be of the form

$$D_i(Q_i) = \frac{1}{2}\pi_i Q_i^2, \tag{20}$$

that is, the marginal damage at a given deposition level Q_i is of the linear form $\pi_i Q_i$.

The structure of the process (4), (5) and (14) is, of course, independent of the form of the cost and damage functions. According to such process, the countries commit themselves to an emissions reduction program in which the marginal values of the cost and damage functions determine the allocation of emission abatement resources among the areas. The realizations of the agreement depend, however, on the functional forms of the cost and damage functions.

By how much does the realization of the process (5), (6), (14) and (18) differ according to whether the damage functions (8) or (20) are used? To answer this question we first need to calculate new values for the parameters π_i, $i = 1, \ldots, 7$. This can be carried out by assuming again that year 1987 describes the noncooperative Nash equilibrium situation, an assumption that allows us to determine the local preferences exhibited by the countries. We get

$$\pi = (1.09,\ 0.09,\ 0.24,\ 0.02,\ 0.12,\ 0.22,\ 0.05) \times 10^6 \text{ FIM}/(10^3\text{ton})^2. \tag{21}$$

The realization of the process can now be simulated by applying, instead of (9), the equation

$$\dot{E}_i = -K(-\alpha_i - 2\beta_i(\bar{E}_i - E_i) + \sum_{j=1}^{n} a_{ji}\pi_j Q_j), E(0) = \bar{E}. \tag{22}$$

The parameters δ_{ij} in the expression (14) for the transfers now depend explicitly on the depositions, and thus on time; they are given as

$$\delta_{ij}(t) = \frac{a_{ij}\pi_i Q_i(t)}{\sum_k a_{kj}\pi_k Q_k(t)}. \tag{23}$$

The emissions abatement program obtained when marginal damages are increasing is one where the total reductions are less important than those obtained with linear damage functions, as one could expect. In the present model the difference is not large however. Kola and Estonia still keep the lion's share in the total abatement (with 74.2 and 43.0 percent reduction, respectively, from their Nash equilibrium emission levels). On the other hand, almost no reduction is taking place any more in the Central Finland and St Petersburg areas.

A new phenomenon occurring here is that for Northern Finland the emissions *increase* along the solution, and reach in the limit a level that is about 12% above their Nash equilibrium level. Moreover, since at the Nash equilibrium $\dot{E}_i$ is necessarily negative for all i's, it is also the case that along the solution the Northern Finland emissions $E_i(t)$ follow a path such that they first decrease and then increase. This can be explained as follows: observe that at the Nash equilibrium the marginal abatement costs C_i' in the various areas are quite different from one another: some may be very high, as is precisely the case with Northern Finland. Observe also that the sum of the marginal damages, $\sum_{j=1}^{n} a_{ji}\pi_j Q_j$, being now an increasing function of the depositions, decreases with the reduction of the latter. Therefore, if at some point t and for some i, the sum of the marginal damages becomes equal to its marginal abatement cost (implying $\dot{E}_i(t) = 0$ for this i), while such equality does not (yet) hold for the other areas $j \neq i$, the reduction in depositions *achieved by these other areas* induce a lowering of $\sum_{j=1}^{n} a_{ji}\pi_j Q_j$ while C_i' does not change, hence a reversal of sign in $\dot{E}_i(t)$.

As far as costs are concerned, from the figures given in Table 7 one observes that the total benefit to be obtained from achieving an optimum decreases to 534 million FIM per year (from 688 million with linear damages). As to the way this aggregate benefit gets shared among the countries involved, it appears that without transfers, Russia is almost indifferent between this optimum and the non cooperative Nash equilibrium, whereas Estonia would be a looser. Note also that the aggregate cost increases in Kola and Estonia, when moving from the Nash equilibrium to the optimum without transfers, are much larger now (+127 and +64, respectively) than with linear damages (+88, resp. +38).

Finally the Chander-Tulkens transfers, that are designed to ensure individual as well as group rationality, appear to be much more favourable to Russia than to Estonia. This is to be explained from formula (23), by taking into account the numerical values of the elements of the transport matrix, the values of the parameters π in the damage functions as re-estimated by (21) in this section, and also the deposition levels Q_i. It is however impossible to disentangle the exact role of each one of these factors in the determination of the transfers that we obtain. Nevertheless, one may note that while Estonia has a rather low value for her π_i, namely 0.05×10^6 in (21), at least two of the three Russian regions have substantially higher ones, namely Karelia (0.12×10^6) and St Petersburg (0.22×10^6). Moreover, although π is very small for Kola, the large depositions Q_i that occur there (see Table 1) weight significantly in (23). These two elements explain that a larger share of the surplus generated by the process goes to Russia rather than to Estonia. The spirit of formula (23) is indeed that the surplus be shared according to the intensity of the marginal damage costs.

The game theoretic "core" property claimed for the Chander-Tulkens cost sharing rule by its authors may also be called upon for explaining the structure of the transfers in the following terms: the amounts of the latter may be seen as reflecting how much is needed to prevent that a country, or group of countries, leave the process and act on their own in the hope of achieving for themselves still larger cost reductions. The figures obtained in the present simulation reflect quite a difference between Estonia and Russia in this respect.

Table 7: Ultimate cost figures (10^6 FIM)
with increasing marginal damages
and Chander-Tulkens transfer scheme

	J_i (eq. (10))	T_i	$J_i + T_i$
Northern Finland	-528	+189	-339
Central Finland	-40	+20	-20
Southern Finland	-33	+16	-17
Finland	**-601**	**+225**	**-376**
Kola	+127	-218	-91
Karelia	-57	+21	-36
St Petersburg	-67	+43	-24
Nearby Russia	**+3**	**-154**	**-153**
Estonia	**+64**	**-71**	**-7**
Total -		-289	
Total +		+289	
Total	-534	0	-534

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